# Upscaling Simple Models for Energetic Shelf Sediment Transport

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## LONG-TERM GOALS

In the context of EuroSTRATAFORM, the long-term goal of this and a closely related project ("The Role of Negative Buoyancy in the Morphodynamics of River Dominated Shelves: A Global Synthesis") is to contribute toward simultaneously understanding (i) short term oceanic processes that erode, transport and deposit sediment in the margin system and (ii) the creation of the preserved stratigraphic architecture, seafloor morphology and sediment facies on continental margins. In order for models at such disparate time-scales to interact, they must communicate through expressions which upscale the underlying physical processes. Under Modeling Task D5, the EuroSTRATAFORM white paper specifically states: "Coherent techniques will be developed for upscaling individual processes/events into long-term stratigraphic-architecture and seascape-evolution models."

Another conclusion common to recent ONR Coastal Geosciences programs is recognition of the dominant role played by episodic, high energy events in driving both sediment transport and bed formation. During STRATAFORM, the majority of across-shelf sediment flux was found to be associated with a few major flood and storm events occurring over just one or two weeks every few years. In its section on modeling, the EuroSTRATAFORM white paper similarly states, "Of special concern will be important events of strata formation (e.g., debris flows, extreme floods) that are difficult to observe." Thus another long-term goal of both this "upscaling" project and its allied "global synthesis" project is to specifically understand the role of energetic sediment transport in depositing sediment on margins and shaping morphology.

## OBJECTIVES

Our work in FY2004 combined a no-cost extension of this "upscaling" project along with the first six months of a closely related project on "The Role of Negative Buoyancy in the Morphodynamics of River Dominated Shelves: A Global Synthesis". The common objectives of these two projects include (1) investigating the role of high energy sediment gravity flows in shelf deposition at multiple time-scales, and (2) investigating the role of these flows in shelf deposition at diverse spatial scales and in diverse settings world-wide.

To help address these objectives at the shortest time- and space-scales, we are applying a wave-resolving, high vertical resolution numerical model with advanced turbulence closure to simulate energetic sediment suspensions. The consistency of the internal structure revealed by these simulations and the bulk formulations applied in our wave-averaged, depth-integrated analytical approach is being examined. Scales are also being bridged from wave-averaged (or "burst-averaged")

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quasi-steady conditions at a single location to deposition through whole flood seasons distributed over entire subaqueous deltas. An important question is whether bulk formulations which work over a period of hours also work over periods of weeks to months. Finally, analytical and simple numerical approaches are being used to upscale these same relations for scenarios where accretion feeds back to impact hydrodynamics. The largest scales compare diverse, globally distributed environments and incorporate subsidence, tectonism and changes in sea level.

**APPROACH**

Seconds to hours: To provide guidance in upscaling realistic turbulence closure models under energetic sediment transport conditions, we are running numerical model simulations of sediment-stratified bottom boundary layers using the 1-D General Ocean Turbulence Model (GOTM, Burchard, 2002). GOTM is an open source, FORTRAN-based, two-equation (k-epsilon) turbulence closure model which uses the most recent formulations for stability functions shown to perform well in the presence of strong thermohaline stratification. We have added suspended sediment to this model and are investigating model behavior as one approaches the limit of critical sediment-induced stratification (Scully and Friedrichs, 2003). We are now systematically examining the parameter space of varying sediment settling velocity ($w_s$) from hindered settling in fluid mud ($w_s < 0.1$ mm/s) to sand ($w_s > 10$ mm/s) and the wave period of the bottom boundary layer from storm waves (order 10 s) to tides (order 10 hours). We are comparing these simulations to available field and laboratory data of very high concentration fluid mud layers within momentum deficit layers under waves (e.g., Eel shelf, Traykovski et al., 2000) and tides (e.g., Amazon shelf, Trowbridge and Kineke, 1994) and of critically stratified constant stress layers of sand under waves (e.g., Hanover Wave Flume, Dohmen-Janssen and Hanes, 2002) and of flocculated mud under tides (e.g., York River, Friedrichs et al., 2000).

Hours to months: The analytical relations governing a wave-supported sediment gravity flow in a wave-averaged, vertically-integrated sense are (Wright et al., 2001; Scully et al., 2002):

$$\alpha\, g\, s\, C\, \rho_s^{-1} = c_d\, |u|\, u_g, \qquad Ri = g\, s\, C\, \rho_s^{-1}\, |u|^{-2} \qquad (1, 2)$$

In Eqs. (1) and (2), $\alpha$ is the sine of the bed slope, g is the acceleration of gravity, $\rho_s$ is the density of siliceous sediment and s is its submerged weight relative to sea water, C is the depth-integrated mass concentration of suspended sediment within the wave boundary layer, $c_d$ is the bottom drag coefficient, and Ri is the gradient Richardson number. The key velocities associated with Eqs. (1,2) are the downslope velocity of the gravity current ($u_g$), the rms amplitude of wave orbital velocity ($u_w$) and the absolute amplitude of the instantaneous velocity, $|u| \approx (u_w^2 + u_g^2)^{1/2}$, all evaluated near the top of the wave boundary layer. By combining (1) and (2), one can solve explicitly for $u_g$ and C and, thus, for the downslope sediment transport rate, $Q_g = u_g C$, and the deposition rate, $D = -\, dQ_g/dx$. It is relatively straightforward to force these equations with observed wave heights and river discharge to predict gravity flow speed, concentration and deposition over observed bathymetry. This has been our approach in modeling gravity flows over hours to entire flood seasons for STRATAFORM and EuroSTRATAFORM field sites (Wright et al., 2001; Scully et al., 2002, 2003; Scully and Friedrichs, 2004; Friedrichs and Scully, 2004b, in prep.).

Years to centuries: We are taking two approaches in upscaling from a season to decades and beyond. The first approach uses predicted deposition (plus any appropriate shifts in base level or sea level) to change the bathymetry and, thus, the hydrodynamics. This quasi-numerical, long time-scale approach follows the same basic philosophy as the hours-to-months simulation, but using annual representative wave heights and discharge, and with bathymetric feedback affecting subsequent hydrodynamics (Friedrichs and Scully, 2004a,b, in prep). Our other long time-scale approach looks for equilibrium analytical solutions to bathymetric profiles consistent with the physics of wave-supported gravity flows. One option in this regard is to define an equilibrium shelf profile as that which causes gravity flows to be just strong enough to carry the riverine sediment supply into deep water without any net deposition (Friedrichs and Wright, 2004). Conceptually, this applies well to a situation where a delta has prograded and steepened to the point that the wave-supported gravity flows now just bypass the shoreward, concave downward portion of the delta, producing no further deposition in this region. Another option is to define as equilibrium a sigmoidal clinoform or subaqueous delta with a fixed profile which progrades across a flat paleo-shelf at a constant rate (Friedrichs and Scully, 2004a,b, in prep). These analytical solutions for shelf profiles employ additional continuity-related equilibrium conditions beyond Eqs. (1)-(2).

## WORK COMPLETED

In FY2004 we continued the process of publishing our related work from the ONR STRATAFORM project (Hill et al., 2004; Parsons et al., 2004). Our newest research efforts in FY2004 focused mainly on the time scales of hours to centuries. Over scales of hours to months, we applied Eqs. (1)-(2) to seasonal flood deposition in the region of the Po subaqueous delta (Figure 1) (Scully and Friedrichs, 2004; Friedrichs and Scully, 2004b, in prep.). Over scales of years to a century, we applied the same equations to the evolution the Po delta since the mid-1800's acceleration in progradation of the Pila distributary (Figure 2) (Friedrichs and Scully, 2004a,b, in prep.). In the context of long-term equilibrium shelf profiles, we finished our first comparison of equilibrium shelf profiles around the world associated with bypassing, wave-supported gravity flows (Friedrichs and Wright, 2004; Pratson et al., 2004a,b). We also derived analytical solutions for similarly force equilibrium prograding clinoforms and applied the solution to the Po shelf (Friedrichs and Scully, 2004a,b, in prep.).

## RESULTS

Figure 1 displays forcing conditions and flood deposition around the Po subaqueous delta as predicted by Eqs. (1)-(2) when applied to the large flood of fall 2000. For the region encompassing the Po subaqueous delta, the equations governing wave-supported gravity flows were implemented in the same manner as that described for the Eel shelf by Scully et al. (2003). Bottom orbital velocity was determined by linear wave theory applied to wave heights observed offshore of Ancona, Italy. Sediment discharge from the Po River before separation into its distributaries was initially estimated by applying the rating curve of Syvitski et al. (2004) for a single river channel neglecting random variability (Figure 1a). Sediment input was reduced to 56% of that predicted by Syvitski et al. (2004) and further restricted to the second half of the flood when discharge and waves occurred together. The along-shelf distribution of sediment used to represent the various distributaries is indicated by the dashed red line in Figure 1b. Results are consistent with the general distribution of the flood layer as mapped by EuroSTRATAFORM investigators and suggest wave-supported gravity flows can account for the majority of the observed deposit. In particular, modeled and observed deposition both occur in deeper water off the Pila than off the Tolle, and, in both cases, maximum deposition occurs near the region of maximum bed slope.

Figure 2 displays results of a long-term simulation of subaqueous delta evolution using Eqs. (1)-(2).

The simulations mimicked profile evolution off of the Pila and Tolle distributary mouths since the mid 1800's. Each case started with the same linearly sloping initial bathymetry and was subjected to the same 1 m wave height and the same rate and spatial distribution of subsidence. The only difference was the rate of sediment input, which was five times larger for the Pila simulation than for the Tolla case. For the Pila case, deposition overwhelmed subsidence, and the subaqueous delta prograded seaward (Figure 2a), reaching a shape and progradation rate very similar to our analytical equilibrium solution. For the Tolle, in contrast, subsidence overwhelmed deposition, and the shoreward portion delta receded landward and steepened (Figure 2b). These results are largely consistent with observed evolution of the Po subaqueous delta since the mid-1800's as reported by Nelson (1970). In the final year of the simulation, maximum deposition occurred in notably deeper water off the Pila than off the Tolle, similar to the patterns seen in observations and simulations of the fall 2000 flood.

In summary, our major results in FY2004 applied our simple model for wave-supported gravity flows to sediment deposition at time scales ranging from a single major flood to steady-state progradation of an equilibrium clinoform. The modeling approach, which limits sediment load via a critical Richardson number, is applicable to fine sediment transport near river mouths wherever wave energy is available to move abundant sediment offshore during floods. Results suggest this phemomena can account for the majority of the fall 2000 flood deposit mapped by EuroSTRATAFORM investigators in the vicinity of the Po subaqueous delta and also for the rate of delta progradation observed off the dominant Pila outlet of the Po over the last 150 years. Model results predict that convergence of down-slope sediment transport by wave-supported gravity flows increases with bed slope but decreases with slope gradient, such that greatest deposition occurs near where steep slopes first stop increasing with distance offshore. Thus on profiles which reach maximum steepness near shore, like those off Tolle-Gnocca-Goro mouths today or off the Pila mouth 150 years ago, gravity-driven deposition occurs in shallower water. Over time, if deposition overwhelms subsidence, the subaqueous delta becomes less steep near shore and steeper offshore, and the locus of deposition moves progressively into deeper water. If the subaqueous delta is prograding across a relatively flat shelf, the form of the prodelta eventually reaches an approximate equilibrium which progrades seaward as a unit.

## IMPACT/APPLICATIONS

A present limitation in long-term modeling of continental margin evolution is realistic inclusion of hydrodynamic processes driving shelf deposition. Based on field observations collected over the last 20 years, complex wave-averaged currents driven by winds and pressure gradients have been thought to be mainly responsible for cross-shelf sediment transport and flux convergence on energetic accretionary shelves. Unfortunately, it may be exceedingly difficult to predict wind- and pressure-driven near-bed currents with sufficient accuracy to produce realistic deposits over geological time-scales. The ONR STRATAFORM and EuroSTRATAFORM projects, however, have identified a distinctly different mechanism for across-shelf mud transport associated with gravity-driven flows of fluid mud within the wave boundary layer. Gravity flows within the WBL can be realistically modeled based on knowledge of fine sediment supply, approximate wave height and bathymetry if one assumes that the critical Richardson number within the WBL determines the maximum capacity of the gravity flow to transport mud. Complex, externally forced mean currents do not appear to play a critical role in this newly identified transport mechanism. Thus the analytical model presented here has the potential to greatly reduce the complexity and computational requirements presently limiting our ability to perform realistic long-term simulations of the geologic evolution of many continental margin environments.

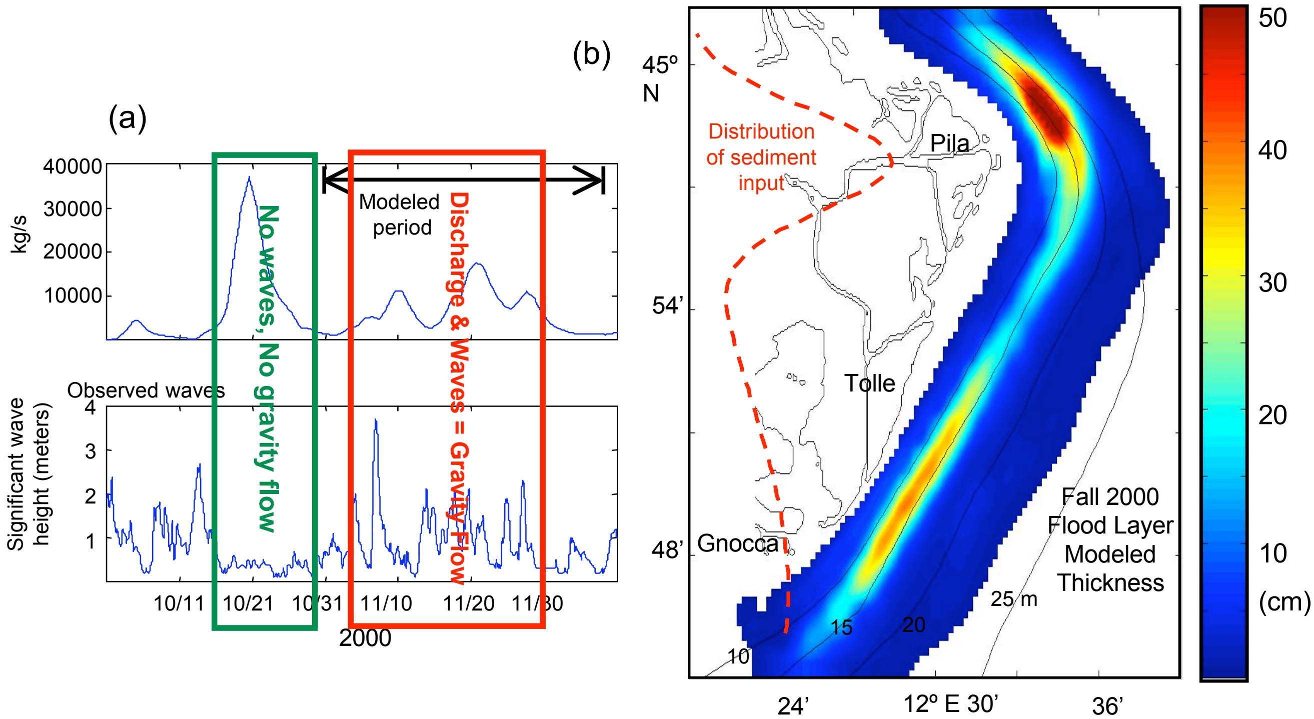


*Figure 1. (a) Forcing conditions for the fall 2000 Po flood simulation. (b) Predicted thickness of the resulting flood layer. Predicted deposition is consistent with the general distribution of the flood layer as mapped by EuroSTRATAFORM investigators.*

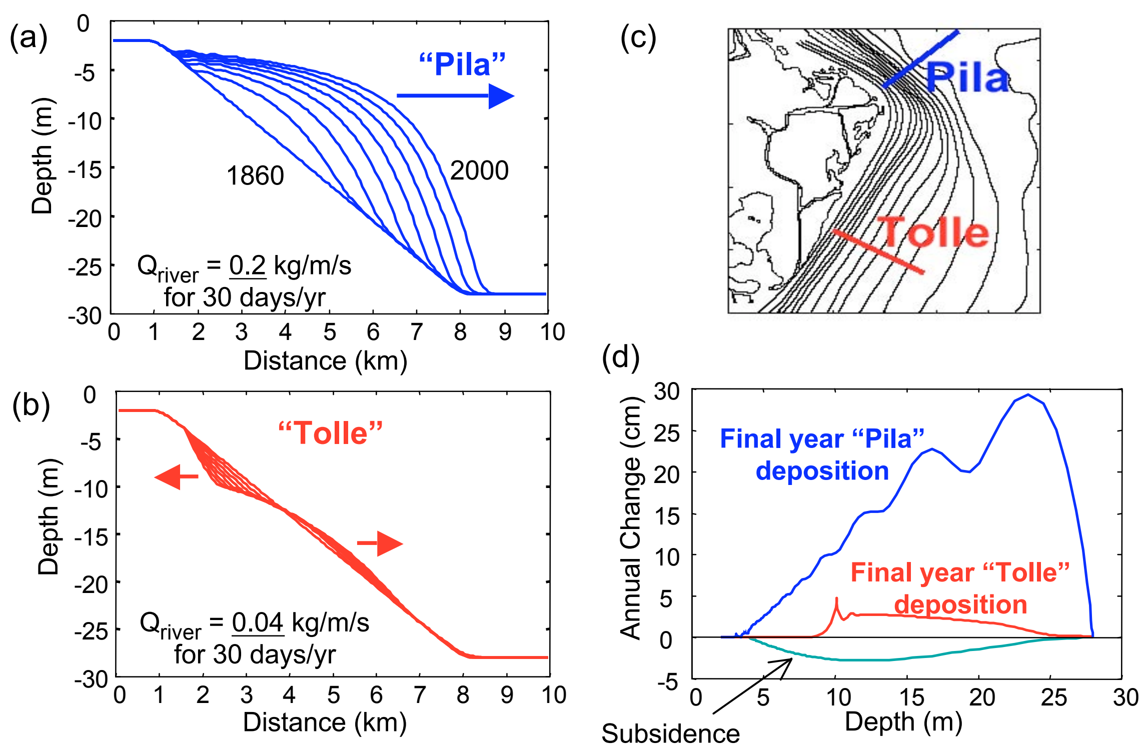


*Figure 2. Evolving bathymetry for simulation of subaqueous delta deposition off of the (a) Pila and (b) Tolle distributaries. (c) Representative profile locations. (d) Predicted deposition during the final year of simulation along with the degree of annual subsidence. Both the long term and final year simulations are largely consistent with observations from the Po subaqueous delta.*

## TRANSITIONS

Our data on bed stresses and resulting sediment resuspension from earlier years of our STRATAFORM project have been made available to others and are being used to verify various bottom boundary layer and sediment transport models. Our data can easily be accessed via data reports (which include data summaries on diskettes) and via the VIMS STRATAFORM website: http://www.vims.edu/physical/projects/CHSD/projects/ONR/index.html. Published papers by others which have directly utilized VIMS data include Morehead and Syvitski (1999), Ogston et al. (1999, 2000), Reed et al. (1999) and Zhang et al. (1999). Additional papers by non-VIMS authors incorporating VIMS data are in preparation. Our analytical formulation for sediment flux and deposition by critically-stratified, gravity flows has already been incorporated into long-term simulations of margin stratigraphic development by James Syvitski's group (Syvitski et al., 2001, 2002). Our analytical approach has also been made available to other modelers, such as Fan, Harris, Niederoda, Reed, Swift, and Traykovski, all of whom are at various stages of incorporating gravity flows into more complex numerical simulations of shelf sedimentation.

## RELATED PROJECTS

The following active projects involving Friedrichs also focus on coastal sediment transport:

1. Forecasting Scour Related Mine Burial Using a Parameterized Model. Office of Naval Research (www.vims.edu/physical/projects/CHSD/projects/MBP).

2. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (www.vims.edu/physical/projects/CHSD/projects/CAREER).

## REFERENCES

Burchard, H., 2002. Applied turbulence modelling in marine waters. Lecture Notes in Earth Sciences, Vol. 100, Springer, Berlin, 229 pp.

Dohmen-Hanssen, C.M., and D.M. Hanes, 2002. Sheet flow dynamics under monochromatic nonbreaking waves. Journal of Geophysical Research, 107 (C3): 13-1 – 13-21.

Friedrichs, C.T., and M.E. Scully, 2004a. Century-scale flow modeling of Po Delta. ONR EuroSTRATAFORM Workshop, Keystone, CO, 10-14 July.

Friedrichs, C.T., and M.E. Scully, 2004b. Modeling deposition by wave-supported gravity flows on the Po River subaqueous delta: from seasonal floods to prograding clinoforms. Sediment Transport and Accumulation on Continental Margins: A Tribute to Dr. Richard W. Sternberg, Friday Harbor, WA, 17-18 September.

Friedrichs, C.T., and M.E. Scully, in prep. Modeling deposition by wave-supported gravity flows on the Po River subaqueous delta: from seasonal floods to prograding clinoforms. For submittal to Continental Shelf Research.

Friedrichs, C.T., and L.D. Wright, 2004. Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths. Coastal Engineering, 51: 795-811

Friedrichs, C.T., L.D. Wright, D.A. Hepworth, and S.-C. Kim, 2000. Bottom boundary layer processes associated with fine sediment accumulation in coastal seas and bays. Continental Shelf Research, 20: 807-841.

Hill, P.S., J.M. Fox, J. Crockett, K.J. Curran, D.E. Drake, C.T. Friedrichs, W.R. Geyer, T.G. Milligan, A.S. Ogston, P. Puig, M.E. Scully, P. Traykovski and R.A Wheatcroft, 2004. Sediment delivery to the seabed on the Eel River continental margin. In: C.A. Nitrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence, in review.

Morehead, M.D., and J.P. Syvitski, 1999. River-plume sedimentation modeling for sequence stratigraphy: application to the Eel margin, northern California. Marine Geology, 154: 29-41.

Nelson, B.W., 1970, Hydrography, sediment dispersal and recent historical development of the Po river delta, Italy. In: Morgan J.P. (ed.), Deltaic Sedimentation, Modern and Ancient. SEPM Special Publication 15: 152-184.

Ogston, A.S. , D.A. Cacchione, R.W. Sternberg, and G.C. Kineke, 1999. Mechanisms of sediment dispersal and the influence of floods on the northern California continental shelf. Coastal Ocean Processes Symposium, a Tribute to William D. Grant, Technical Report WHOI-99-04, Woods Hole Oceanographic Institution, Woods Hole, MA, p. 171-174.

Ogston, A.S., D.A. Cacchione, R.W. Sternberg, and G.C. Kineke, 2000. Observations of storm and river flood-driven sediment transport on the northern California continental shelf. Continental Shelf Research, 20: 2141-2162.

Parsons, J.D., C.T. Friedrichs, P. Traykovski, D. Mohrig, J. Imran, J.P.M. Syvitski, G. Parker, P. Puig and M.H. Garcia, 2004. The mechanics of marine sediment gravity flows. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence, in review.

Pratson, L., J. Swenson, A. Kettner, J. Fedele, G. Postma, A. Niedoroda, C. Friedrichs, J. Syvitski, C. Paoloa, M. Steckler, E. Hutton, C. Reed, M. Van Dijk, and H. Das, 2004b. Modeling continental shelf formation in the Adriatic Sea and elsewhere. Oceanography, in review.

Pratson, L., P. Wiberg, M. Steckler, D. Cacchione, J. Karson, E. Mullenbach, J. Swenson, C. Nittrouer, B. Murray, G. Spinelli, C. Fulthorpe, D. O'Grady, G. Parker, N. Driscoll, R. Burger, C. Paola, D. Orange, M. Wolinsky, M. Field, C. Friedrichs, and J. Fildelez, 2004a. Seascape evolution on clastic continental shelves. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence, in review.

Reed, C.W., A.W. Niedoroda, and D.J.P. Swift, 1999. Modeling sediment entrainment and transport processes limited by bed armoring. Marine Geology, 154: 143-154.

Scully, M.E., and C.T. Friedrichs, 2003. Numerical modeling of wave- and tide-supported, critically-stratified high energy suspensions using GOTM k-epsilon turbulence closure. ONR EuroSTRATAFORM Annual Meeting, Aix-en-Provence, France, 26-29 October.

Scully, M.E., and C.T. Friedrichs, 2004. Modeling wave-supported gravity-driven transport: Po River delta, 2000. ONR EuroSTRATAFORM Workshop, Keystone, CO, 10-14 July.

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2002. Application of an analytical model of critically stratified gravity-driven sediment transport and deposition to observations from the Eel River continental shelf, northern California. Continental Shelf Research, 22: 1951-1974.

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2003. Numerical modeling results of gravity-driven sediment transport and deposition on an energetic continental shelf: Eel River, Northern California. Journal of Geophysical Research, 108 (C4): 17-1 – 17-14.

Syvitski, J.P.M., C. Friedrichs, P. Wiberg, and C. Reed, 2001. Representing Shelf Bottom Boundary Transport in 2D-SedFlux: Stratigraphic Formation on Continental Margins. Annual Conference of the International Association for Mathematical Geology, Cancun, Mexico, 6-12 September.

Syvitski, J.P.M, E.W.H. Hutton, C. Friedrichs, P. Wiberg and C. Reed, 2002. Coupled land-sea numerical sediment-transport models and the formation of shelf stratigraphy IAS/SEPM Environmental sedimentology Workshop on Continental Shelves, Hong Kong, 7-10 January.

Traykovski, P., W.R. Geyer, J.D. Irish, and J.F. Lynch, 2000. The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. Continental Shelf Research, 20: 2113-2140.

Trowbridge, J.H., and G.C. Kineke, 1994. Structure and dynamics of fluid muds on the Amazon continental shelf. Journal of Geophysical Research, 97: 865-874.

Wright, L.D., C.T. Friedrichs, S.C. Kim, and M.E. Scully, 2001. Effects of ambient currents and waves on gravity-driven sediment transport on continental shelves. Marine Geology, 175: 25-45.

Zhang, Y., D.J.P. Swift, S. Fan, A.W. Niedoroda, and C.W. Reed 1999. Two-dimensional numerical modeling of storm deposition on the northern California shelf. Marine Geology, 154: 155-167.

**PUBLICATIONS**

Friedrichs, C.T., and L.D. Wright, 2004. Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths. Coastal Engineering, 51: 795-811 [published, refereed].

Friedrichs, C.T., L.D. Wright, D.A. Hepworth, and S.-C. Kim, 2000: Bottom boundary layer processes associated with fine sediment accumulation in coastal seas and bays. Continental Shelf Research, 20: 807-841 [published, refereed].

Hill, P.S., J.M. Fox, J. Crockett, K.J. Curran, D.E. Drake, C.T. Friedrichs, W.R. Geyer, T.G. Milligan, A.S. Ogston, P. Puig, M.E. Scully, P. Traykovski and R.A Wheatcroft, 2004. Sediment delivery to the seabed on the Eel River continental margin. In: C.A. Nitrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.) Continental Margin Sedimentation: Transport to Sequence [submitted, refereed].

Kim, S.C., C.T. Friedrichs, J.P.-Y. Maa, and L.D. Wright, 2000. Estimating bottom stress in a tidal boundary layer from acoustic Doppler velocimeter data. ASCE Journal of Hydraulic Engineering, 126: 399-406 [published, refereed].

Parsons, J.D., C.T. Friedrichs, P. Traykovski, D. Mohrig, J. Imran, J.P.M. Syvitski, G. Parker, P. Puig and M.H. Garcia, 2004. The mechanics of marine sediment gravity flows. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence [submitted, refereed].

Pratson, L., J. Swenson, A. Kettner, J. Fedele, G. Postma, A. Niedoroda, C. Friedrichs, J. Syvitski, C. Paoloa, M. Steckler, E. Hutton, C. Reed, M. Van Dijk, and H. Das, 2004. Modeling continental shelf formation in the Adriatic Sea and elsewhere. Oceanography [submitted, refereed].

Pratson, L., P. Wiberg, M. Steckler, D. Cacchione, J. Karson, E. Mullenbach, J. Swenson, C. Nittrouer, B. Murray, G. Spinelli, C. Fulthorpe, D. O'Grady, G. Parker, N. Driscoll, R. Burger, C. Paola, D. Orange, M. Wolinsky, M. Field, C. Friedrichs, and J. Fildelez, 2004. Seascape evolution on clastic continental shelves. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence [submitted, refereed].

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2002. Application of an analytical model of critically stratified gravity-driven sediment transport and deposition to observations from the Eel River continental shelf, northern California. Continental Shelf Research, 22: 1951-1974 [published, refereed].

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2003. Numerical modeling results of gravity-driven sediment transport and deposition on an energetic continental shelf: Eel River, Northern California. Journal of Geophysical Research, 108 (C4): 17-1 – 17-14 [published, refereed].

Souza, A., and C. Friedrichs, 2005. Sediment effects. In: H. Baumert, J. Simpson, and J. Sündermann (eds.), Marine Turbulence: Theories, Observations and Models. Cambridge University Press, Cambridge, UK [in press, refereed].

Wright, L.D., C.T. Friedrichs, S.C. Kim, and M.E. Scully, 2001. Effects of ambient currents and waves on gravity-driven sediment transport on continental shelves. Marine Geology, 175: 25-45 [published, refereed].

Wright, L.D., C.T. Friedrichs, and M.E. Scully, 2002. Pulsational gravity-driven sediment transport on two energetic shelves. Continental Shelf Research, 22: 2443-2460 [published, refereed].

Wright, L.D., S.-C. Kim, and C.T. Friedrichs, 1999. Across-shelf variations in bed roughness, bed stress and sediment transport on the northern California shelf. Marine Geology, 154: 99-115 [published, refereed].

**HONORS/AWARDS/PRIZES**

Friedrichs, C.T., 2000. Faculty Early Career Development (CAREER) Award. Awarded by the National Science Foundation (NSF). Description from NSF website: The CAREER Award is NSF's most prestigious award for new faculty members. The CAREER program recognizes and supports the early career-development activities of those teacher-scholars who are most likely to become the academic leaders of the 21st century.

Friedrichs, C.T., 2000. Presidential Early Career Award for Scientists and Engineers (PECASE). Awarded by President Clinton. Description from PECASE website: The PECASE Award is the highest honor bestowed by the United States government on young professional at the outset of their independent research careers. Eight Federal departments and agencies join together annually to nominate the most meritorious young scientist and engineers who will broadly advance the science and technology that will be of the greatest benefit to fulfilling the agencies' missions.

Friedrichs, C.T., 2001. Class of 1964 Distinguished Professorship. Awarded by the College of William and Mary. From William and Mary memo: Distinguished professorships for associate professors are designed to recognize and reward excellence in research or creative activity and a demonstrated commitment to teaching, and to encourage faculty to remain at the College. Recipients of these professorships will already enjoy a reputation for excellence in scholarship and teaching which suggests that they may be candidates for other distinguished professorships in the future.